Problems of open discharge: Notes to publications

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The discussion concerning the mechanism of open discharge is summarized. Basic arguments in favor and against the photoelectron nature of the open discharge, including those not published yet, are analyzed. Simple and consistent estimates of the photoelectron contribution to the efficiency of electron beam formation in the open discharge are presented for the first time. It is proved that the open discharge is a sort of the glow discharge.

The abnormally high efficiency of electron beam (e-beam) formation in the open discharge (OD) with a grid anode makes the basis for the statement that OD is a new type of discharge, namely, the photoelectron discharge sustained by photoemission from a cathode, and this attracts considerable attention to the OD mechanism. In my opinion, the series of papers[1–6] is sufficient to answer the question on whether the OD is a photoelectron discharge or a sort of the glow discharge? These papers have demonstrated the inconsistency of all principal statements put forward in favor of the photoelectron OD and presented the calculations of the atom–electron emission from a cathode in OD, which confirm the decisive contribution of this emission. However, the papers in favor of the photoelectron mechanism of OD still continue to be published.

So the first part of this paper reviews briefly the background of the issue and analyzes the basic arguments in favor and against the photoelectron nature of the OD from different publications, including those not mentioned in Refs. 1–6.

The second part presents, for the first time, a very simple and consistent estimates of the contribution of photoelectrons to the total emission of electrons from the cathode. These estimates are compared with the calculated[1] contribution of the atom–electron emission (from ionized γ_i and neutral γ_a atoms). The comparison of these contributions suggests finally that OD is a sort of the glow discharge, which, as known, is sustained by gas ionization and atom–electron emission from the cathode.

The aspects important for the glow discharge in general are emphasized everywhere. The most significant issues, as well as those missed in Refs. 1–6, are considered in a more detail. Discharge in helium is considered unless otherwise specified.

1. Analysis of publications concerning the mechanism of open discharge

1.1. The detailed studies of the discharge with a grid-type anode, which was then called the open discharge, have started from publications of Refs. 7 and 8. A similar discharge with different shapes of the grid openings was known before, in particular, the discharge with a hollow anode (one opening in the anode) is used for a long time in technological electron guns.[9] The coaxial version of the design with a grid-type anode was also proposed earlier in Ref. 10 for excitation of cw gas-discharge lasers. The working gas pressure in OD was increased up to several tens of Torrs due to small discharge gaps $d = 0.5$–1 mm and grid-like anodes with holes $A \le 0.5$ mm, and this extended the OD capabilities in excitation of gas media.[11]

The initial interpretation of the OD mechanism consisted in the following.[12] In the electron avalanche initiated by an electron emitted from the cathode, only a fraction k of the electrons ($k < 1$) is generated in the strong field of the cathode drop (CD) and can be converted into runaway electrons. The N_i number of ions generated in such a way move to the cathode and eject γN_i electrons, which also become runaway electrons. Therefore, the limiting efficiency of generation of runaway electrons can be estimated as follows:

$$\eta = \mu\xi = \mu\,(kN_i + \gamma N_i)/(\gamma N_i + N_i) = \mu\,(k + \gamma)/(\gamma + 1), \qquad (1)$$

where ξ is the efficiency inside the gap d; μ is the geometric transparency of the grid-like anode; γ is the generalized coefficient of electron emission from the cathode under bombardment of the cathode surface by ions, photons, etc. Kolbychev and Samyshkin[12] believed that, under typical conditions of glow discharge, $\gamma \approx 0.2$ and the size of the cathode drop is smaller than the electron mean free path. Therefore, $k \approx 0$ and $\eta \le 17\%$. Hence, to explain the practically achieved high efficiency $\eta \approx \mu$ in OD, it should be believed that the transient discharge stage generating the beam, when k is close to unity, is restricted in time by the instant of formation of the cathode drop. It was stated that this stage is not a glow discharge, since it has no any pronounced cathode drop region. The existence of this stage is possible only if electrons are continuously accelerated all over the discharge gap, that is, when $E/p > (E/p)_{cr}$ [for helium $(E/p_{He})_{cr} = 150$ V/(cm · Torr)].

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Thus, it follows from Ref. 12 that the efficient e-beam generation in OD is possible only in the absence of the cathode drop.

However, in Ref. 13 it has been demonstrated that $\eta \approx \mu$ under optimal OD conditions regardless of the presence of the cathode drop. Then, according to Eq. (1), electrons must be generated largely on the cathode surface and γ must be $\gg 1$. In this case, $\eta \approx \mu$ even at $k = 0$. In Ref. 12, as well as in Ref. 13, the experiments evidenced the important role of photoprocesses in OD formation. This is not surprising, because, unlike the discharge with solid electrodes, OD has an e-beam drift region, from which the discharge gap is additionally illuminated. The drift volume can be 100 times as large as the volume of the gap. Based on this fact and indirect experiments, in Ref. 13 it was assumed that $\gamma \gg 1$ is provided by cathode illumination from the drift region. This assumption has gained common acceptance, and the discharge has been called the open discharge. Starting from this publication, the parameter η, which can be expressed through the e-beam current measured with a collector j_c and the anode current j_a as

$$\eta = j_c / j = j_c / (j_c + j_a) = \mu\xi = \mu\, j_e / (j_e + j_i) \qquad (2)$$

(j_e, j_i are the e-beam and ion currents inside d), was identified as the efficiency measured by calorimeters in technological electron guns.[9]

1.2. In Ref. 13 we have also considered the issue very important for revealing the OD mechanism: the distribution of potential over d. To explain the appearance of an e-beam formed in the layer of ion charge exchange behind the grid-like cathode at alternation of the OD sign, it was supposed that the length of the cathode drop l_{cf} at sufficiently high currents can be $\sim\lambda_{ct}$ (the length of ion charge exchange), and the applied voltage U is concentrated in the cathode drop region. The measurements of the potential distribution[14] in the gap $d = 1$ mm wide with the grid probes arranged with the intervals of 0.2 mm turned out to agree to this supposition.

In Ref. 15 and then in Ref. 16, some doubts were cast upon the assumptions of Ref. 13 and measurements in Ref. 14. In Ref. 15 the inadmissibly high cathode fields at $l_{cf} \sim \lambda_{ct}$ were noticed, and in Ref. 16, based on the experiments from Ref. 17, it was noted that the parameters of discharge after the initial transient process are automatically determined by the gap between the cathode and the closest probe grid. Finally, the measurements of the field distribution over d using polarization spectroscopy in Ref. 18 (in Ref. 18 it was not mentioned at which phase of the current pulse the measurements were conducted, but in Ref. 19 it was directly shown that the degrees of polarization for the spectral lines were determined at the line peaks, consequently, near the current peak, rather at its leading edge, as was stated in Ref. 20) and the potential in Ref. 21 by the probe method different from that used in Ref. 14 have shown that $l_{cf} \gg \lambda_{ct}$, and outside the CD region there is the field many times exceeding the $(E/p)_{cr}$. The distribution of radiation of some He lines over d also indicates that $l_{cf} \gg \lambda_{ct}$ (Ref. 22). The presence of a rather strong field all over the gap d can be fixed without measuring the field distribution in it. For this purpose, we should check that the current of the abnormal discharge[23]:

$$j_{AD} = 2.5 \cdot 10^{-12}\, p^2 (U_{cf})^3 \qquad (3)$$

(the equation is derived for helium), equivalent to j_{AD} in the discharge with CD U_{cf} equal to the discharge voltage U, significantly exceeds the measured current $j_{AD}/j \gg 1$ (either CD is not fully formed or the significant part of U drops outside the CD region, beyond l_{cf}). From Table 2 in Ref. 20, it follows that in the OD region the condition $j_{AD}/j \gg 1$ is usually fulfilled and, consequently, the strong field is present in the entire gap d. In Ref. 23 it has been demonstrated that in the quasistationary OD, if $d \geq (l_{cf})_{AD}$ – the minimum length of the CD region in the abnormal discharge

$$(pl_{cf})_{AD} = 0.37 (pl_{cf})_n, \qquad (4)$$

where $(pl_{cf})_n$ is taken for the normal glow discharge (Eq. (4) is valid for any gas), then the law of similarity (3) is true in a wide range of the parameter pd magnitude. For He we can take

$$(p_{He} l_{cf})_{AD} \approx 0.48 \text{ Torr} \cdot \text{cm}. \qquad (5)$$

Since U_{cf} was not measured in the experiments, the discharge voltage U was substituted for the experimental data in Eq. (3). From the plot presented in Ref. 23 it can be seen that for the fixed value of pd in the experiments with the increase of U, the discharge current becomes lower than that calculated by Eq. (3) (up to two-fold difference). That is, even in this case a significant fraction of U is concentrated on the discharge plasma outside the CD region. However, in Ref. 20 it is stated that the conditions of the discharge in Ref. 23 are far from those typical of the OD. The comparison of the basic initial parameters p, d, and U from Ref. 23 (for example, $p = 9.8$ Torr, $d = 0.5$ mm, $U = 1.7$–6 kV) and from Tables 1 and 2 in Ref. 20 for typical OD shows their close agreement for about one third of the experiments in Ref. 23. The higher current in Ref. 23 is achieved in the process of gradual development of the discharge to the quasistationary stage, which was not studied earlier for similar conditions in OD. Later on in Ref. 2 it has been demonstrated for $d = 26$ mm that the parameter η close to μ is achieved as the parameter pd reaches 25 Torr · cm, that is, under conditions of the right-hand branch of the Paschen curve far from its minimum $(p_{HE}\, d)_{min} \approx 4$ Torr · cm, when the openings in the anode exert no effect on the discharge.

So the data presented indicate that, under typical OD conditions, $l_{cf} \gg \lambda_{ct}$ and the strong field sufficient for electron runaway is present all over the discharge gap.

However, in Ref. 20 the measurements of the potential distribution in Ref. 21 were criticized and it was concluded that the field in the gap at the dense stage of OD ($j > 1$ A/cm^2) is concentrated in a very narrow area near the cathode, and the length of this area can be much shorter than the limiting length of the CD region of the abnormal discharge, up to the ion mean free path. In Ref. 20 it was also noted that similar violations of Eq. (4) were observed by other authors and the discharge in deuterium $p = 0.079$ Torr (stainless steel cathode) from Ref. 24 was presented as an example. But Ref. 20 presents incorrect estimates. Actually, for hydrogen and a cathode from Fe in Ref. 25 $(pl_{cf})_n = 0.9$ Torr · cm and, according to Eq. (4), $(pl_{cf})_{AD} = 0.33$ Torr · cm. In Ref. 24 for $U = 40–80$ kV used in the experiments, the following empirical equation is presented: $pl_{cf} = 0.216$ Torr · cm, that is, only 1.5 times lower than follows from Eq. (4), rather than $pl_{cf} \ll (pl_{cf})_{AD}$. In Ref. 20 it is stated that the measurements in Ref. 24 have been made at low electric current $j = 0.22$ A/cm^2. In fact, the current for the considered pressure is very high – 5 orders of magnitude higher than the current of the normal glow discharge.[25]

Let us demonstrate[6] that in OD the condition $l_{cf} \sim \lambda_{ct}$ cannot be fulfilled. The typical time of beginning of explosive processes on the cathode in vacuum under the electric field strength $E_c \approx \approx 10^6$ V/cm is about few nanoseconds.[26] In Ref. 9 it was noted that the vacuum breakdown occurs at $E_c = 3–5 \cdot 10^5$ V/cm. The discharge of the duration $\tau \approx 100$ ns in a tube with a mechanically polished Al cathode transforms to spark at $E_c = (0.5–1) \cdot 10^5$ V/cm, and with the electrochemically polished Mo cathode this takes place at $E_c = 4.5 \cdot 10^5$ V/cm (Ref. 23). In the typical OD (oscillograms in Fig. 3 in Ref. 20) $p_{He} = 30$ Torr, $U = 5.5$ kV at the peak current $j = 35$ A/cm^2 (the equivalent current j_{AD} would be 370 A/cm^2) with the duration $\tau \approx 100$ ns. Assuming the charge exchange cross section $\sigma_{ct} = 10^{-15}$ cm^2, for the field near the cathode surface, if $l_{cf} \sim \lambda_{ct}$, we obtain $E_c \approx 2U/l_{cf} = 2U\sigma_{ct}N_a = 10^7$ V/cm. Under conditions of the experiments in Ref. 21 ($p_{He} = 20$ Torr, $U = 7.8$ kV, $j = 45$ A/cm^2), the calculated field, if $l_{cf} \sim \lambda_{ct}$, also equals to 10^7 V/cm, when the spark breakdown of the gap is unavoidable. At the same time, the field measured in Ref. 21 $E_c = 2.7 \cdot 10^5$ V/cm is quite acceptable, and at higher fields we should expect discharge sparking, which indicates the correctness of the measurements of the field distribution in Ref. 21. In Ref. 20 it was noticed that discharge sparking was absent in the probe measurements in Ref. 14. But, is must be absent, because for the separation of 0.2 mm between the cathode and the nearest probe grid and $p_{Ne} = 4.6$ Torr, according to Eq. (4), $(l_{cf})_{AD} > 0.2$ mm, the field opposite to the grid bridges is slightly distorted and at the highest $U = 5$ kV used in the experiments the field near the cathode is $E_c = 2.5 \cdot 10^5$ V/cm, which is also quite acceptable. But this is not the case, if the field is concentrated within the length of ion charge exchange, when $E_c = 2.2 \cdot 10^6$ V/cm.

Thus, the experiments show that $l_{cf} \sim \lambda_{ct}$ in OD cannot be established because of the beginning of the explosive processes on the cathode. In addition, if OD is a photoelectron discharge, a question arises: what is the source of ions that fully screen the field in the gap outside $\sim\lambda_{ct} \ll (l_{cf})_{AD}$ at the total OD current one to two orders of magnitude lower than in the abnormal discharge, when the e-beam current, according to the estimates from Ref. 20, can exceed the ion current by 40 and more times [in accordance with Eq. (2) $j_e/j_i = \xi/(1-\xi)$]?

1.3. In Ref. 4 I have considered the important issue concerning the measurements of the efficiency in OD, which is closely connected with the justification of the OD mechanism. All the recent attempts to prove the photoelectron nature of OD reduced to the algorithm: if, according to the calculations, the ion–atom emission of electrons from the cathode fails to provide for the high value of the parameter η, then it must be *a priori* provided by the photoemission, whose contribution remained undetermined[21,27] (the calculation made in Ref. 20 will be discussed below). The corresponding calculations either ignored electron emission under the effect of fast neutral atoms[28] generated in the charge exchange process or estimated ξ in Eq. (1) by the equation[21,27]

$$\xi = \gamma N_i (\gamma N_i + N_i)^{-1} = \gamma(\gamma + 1)^{-1}, \qquad (6)$$

ignoring the e-beam generated in the gap volume ($k = 0$), which understated the calculated value of η. It is worthy to note that the incorrectness of direct comparison of the parameter η with the efficiency of traditional electron guns having anode plasma,[9,29] in which the efficiency is measured by calorimeters and thus the beam energy is estimated rather than its current. These parameters are identical, if OD actually has the photoelectron nature.

In Section 1.2 it has been shown that under typical OD conditions the strong field is present all over the discharge gap regardless of the presence of the CD region there. In this case, all electrons generated in the gap volume can experience continuous acceleration, that is, as was supposed in Ref. 12 for the undistorted field in d. Consequently, the coefficient k in Eq. (1) is close to unity, and $\eta \approx \mu$, which is usually observed under optimal OD conditions and, what is important, in this case η is independent of the value and nature of γ. For the simplest discharge[2,3,22] with the field slightly distorted by charges, when the current through the grid bridge is low, $\eta \approx \xi \approx 1$. (The parallelism of the field lines in the gap is distorted by the field sag in the anode grid, and the ions generated in this weakened field are focused onto the cathode along the axes of the openings in the grid. This effect is used in electron guns with a hollow anode to obtain narrow e-beams,[9] in which the beam diameter can be an order of magnitude smaller than the diameter of the anode opening. The same is observed in the pulsed mode of OD at its initial stage even at small value of *pd* [Fig. 3 in Ref. 20]. Such modes and stages of the discharge are not phantom, as was stated in Ref. 20. The attempts undertaken in Ref. 20 to explain this effect, conflicting with the photodischarge, from other points are far from the real discharge conditions.) Certainly, if there is a region of weak field behind the CD region, then γ should be taken into account as in Eq. (6).

To measure the e-beam current with a collector was proposed under vacuum conditions. In the presence of a gas, the collector can respond not only to the e-beam current, but also to the drain current of additional charges produced in the drift region or even the current of the formed discharge to it. This situation likely arises in measuring the e-beam current by a collector in OD with the complex geometry of the discharge gap,[27,30,31] which is discussed in detail in Ref. 4.

Thus, high efficiency of e-beam generation, determined as the ratio of the beam current to the total current, cannot serve a proof of one of the OD mechanisms and is the true criterion of the radiant efficiency of the beam. When measuring the e-beam current, one should keep in mind that the collector can respond not only the e-beam current, but also the current of the direct discharge to the collector. If charges are separated by the field near the cathode surface after γ-processes or after the events of ionization in the gap volume, then the movement of charges, ions, and electrons to the external power supply is measured as a collector current, if the electrons reach the collector, even if these electrons acquire the negligibly low velocity during their passage.

1.4. In Ref. 32, Kolbychev revises the mechanism of cathode illumination in OD. Noting that the stage of generation of the pulsed e-beam is short and that the illumination geometry worsens and the energy deposited into the medium (UV radiation) decreases with the increase of the applied voltage, because the beam electrons more weakly interact with the gas, Kolbychev has concluded that the UV illumination ensuring the photoelectron character of OD results from de-excitation of the atoms excited by the current j_g to the anode grid, which compensates for the charge carried by the e-beam into the drift space, rather than by the e-beam. If the first part of this conclusion fully agrees with the position upheld by me for a long time,[33] then the second part is hard to agree with. Questions arise: why does the OD current keeps unchanged as the drift length varies, say, by an order of magnitude? What to do with the quasistationary or continuous OD, when $j_g = 0$? Although these contradictions were noticed in Ref. 1, Kolbychev in his next paper[21] again confirmed his conclusion from Ref. 32. Finally, note that OD was specially developed for excitation of lasers, but, as follows from Ref. 32, the compensating currents, like ordinary discharge currents, excite atoms better than e-beams. So it seems that the easier way is to refuse from these beams and use only the ordinary discharge for excitation of lasers.

In spite of the mentioned obvious contradictions, additional investigations have been carried out,[5] in which the effect of the compensating currents on OD was revealed by comparing the behavior of the total OD current in the cases of the collector connected to the anode and disconnected from it (collector at the free potential; the whole e-beam current becomes compensating, and j_g increases by orders of magnitude). For $p > 10$ Torr, the collector disconnection did not change the discharge parameters. As p decreased, the collector disconnection was accompanied by the increase in the lag of the electrical breakdown of the gap d until the breakdown disappeared due to the partial compensation for field sagging from the gap d behind the grid by the field of the negative charge deposited on the collector at the pre-breakdown stage of the discharge. The effect of e-beams on OD was also observed in the experiments.

The main conclusion of Ref. 5 was that the compensating currents or e-beam currents do not ensure the photoelectron mechanism.

In the experiments described in Ref. 34, an additional grid connected to the anode was placed near (2 mm) the grid-like anode, outside the accelerating gap. The non-self-maintained auxiliary discharge (U = 0–35 V) between this grid and the collector (separated by 20 mm, plus pole at the collector) was accompanied by the increase of the current in the accelerating gap up to two times, which presumably was caused by additional illumination from this auxiliary discharge (again the question arises: what for the e-beams are needed in excitation of lasers?).

In the experiments, the current in the accelerating gap was an order of magnitude lower than that required by Eq. (3) for establishing the completely formed CD, that is, the discharge worked at the sag of the field, which was under strong effect of the conditions near the anode grid, for example, the presence of additional electrodes or foreign sources of charged particles there, and others. Let us give an example. If in the nearly simplest mode we touch the discharge tube by a grounded electrode or carry it to the discharge from the side of drift near the grid, then the distribution of the sagged field there changes, the current decreases [Fig. 1, Ref. 35] and the discharge can even dye out (it is interesting how this effect can be attributed to photodischarge?).

Actually, as was shown in Ref. 3, the increase of the current in Ref. 34 was caused by the field of the auxiliary discharge (E/p = 0–1.1 V/(cm · Torr)), which produced an additional ion flux to the grids. Then this flow was caught up by the field sagged from the accelerating gap, which amounts to E/p = 0.95 V/(cm · Torr) at the place of location of the additional grid, according to the calculation. Note that the parameter E/p here is close to $E/p \approx 1$ V/(cm · Torr) in the positive column of the normal glow discharge. Similar experiments in Ref. 20 with the same effect but the alternated sign of the auxiliary discharge (minus sign at the collector) do not find that simple explanation; it is necessary to know the experimental details and the field distribution near the grid electrodes and between them. However, it can be noted that at the same current the disconnection of the collector (with the minus charge due to the deposited charge) in the experiments with the compensating currents did not change the discharge parameters.

In Ref. 20, the current and the parameter η were measured depending on the cathode area occupied by the charge. The area S was varied (S = 0.014–1 cm^2) by covering the part of the cathode with a mica plate with an opening and the thickness less than d = 1 mm. The grid part of the anode had the same area S. The drop of j and η with the decrease of S, which was explained in Ref. 20 by worsening of the geometry of the cathode illumination from the drift space, is actually caused by the edge effects. Near the boundary of the opening in mica, the lines of field are deflected and the cathode area occupied by the discharge narrows, which can be clearly seen in Fig. 2 from Ref. 4 obtained under similar conditions. Therefore, j decreases with decreasing S. Since in Ref. 20 U = 1.5–1.9 kV, $p \approx 2$ Torr (according to Eq. (5) l_{cf} = 2.4 mm > d), and the mica plate deflects the field near the cathode, the e-beam diverges near the opening edges. This results in a drop of η with the decreasing S because of the increase in the relative scattering of the e-beam to the solid part of the anode.

1.5. Consider again Ref. 20, which, in its authors' opinion, easily interprets the arguments contradicting the photoelectron nature of OD from the position of the photoelectron mechanism. Consider then with the numbers, as in Ref. 20 (5.3.1–5.3.4), but first let us analyze the calculated photoemission coefficient γ_v (Table 1 (TABLE 1) in Ref. 20) (the calculations themselves are missing in Ref. 20).

Let us make our analysis from the positions of Ref. 20 and consider whether or not these results contradict the basic supposition of Ref. 20 about the photoelectron nature of the OD. Consider typical OD conditions, under which $\eta \approx \mu$. In accordance with the conclusions of Ref. 20, we assume that the ion current is low, roughly 40 times lower than the e-beam current, and the contribution to the emission from the cathode bombardment by heavy particles is negligibly low. As in Ref. 20, γ_v is understood as the number of electrons ejected from the cathode by the radiation generated at the deceleration of a single electron. For the photodischarge, $\eta \approx \mu$ and the condition of the self-maintained discharge are fulfilled automatically, if $\gamma_v > 1$ and the ion current is low.

In Ref. 20, γ_v is the sum of the contributions from different processes in the discharge gap d and in the drift space. Since the efficiency of excitation and ionization of atoms by electrons are close in value, to keep the efficiency of e-beam formation high, $\eta \approx \mu$ ($\xi \approx 1$), the contributions to γ_v from the processes of atom excitation in d (according to TABLE 1: γ_4 is due to the fast electrons scattered elastically and inelastically from the anode grid, γ_5 is due to the electrons from the secondary electron emission from the anode, γ_6 is due to the electrons of the e-beam in the gap and the secondary electrons accelerated in the gap) and in the region of field sagging behind the anode grid (γ_3) must be negligibly small as compared with $\gamma_v \gg \gamma_d = \gamma_3 + \gamma_4 + \gamma_5 + \gamma_6$, even if by 40 times. Their large contribution is automatically accompanied by the high ion current to the cathode, during which η must drastically decrease, in Bokhan and Bokhan's opinion.

According to TABLE 1, the highest ratio γ_v/γ_d = 5.1 is quite small and takes place in one of nine cases, being much smaller in all other cases. For example, in the beginning of the current pulse, when $\eta = \xi = 1$, the oscillograms are given in Fig. 3 of Ref. 20, γ_v/γ_d = 1.1. (By the way, it should be noted that Ref. 20 gives γ_p = 0.15–0.2 for the coefficients of photoemission from the surface of different metals. Actually, for the resonant emission of He, which is responsible for the largest contribution to the photoemission, γ_p = 0.1–0.13 for Fe, Al, Mo, and Cu cathodes used in OD.[36] So, if looking at TABLE 1, it may be problematic to ensure the calculated values to be $\gamma_v > 1$).

These contradictions are indicative of the wrong approach used in Ref. 20 to explain the mechanism of OD. Nevertheless, let us discuss Sects. 5.3.1–5.3.4 from Ref. 20. As before, let us again perform the consideration from the positions of Ref. 20 and neglect the already found contradictions.

1) Consider the discharge illustrated by the oscillograms in Fig. 3 in Ref. 20. At the very beginning of the current pulse, when U = 7.8 kV, the main channel of photon income to the cathode is caused by the sag of the field: γ_3 = 0.96 (γ_v = 1.7, row 5′ of TABLE 1). Then $l_{cf} \sim \lambda_{ct}$ is quickly established (the amplitude value of the current achieves 35 A/cm^2), the sag of the field vanishes, and another main channel caused by the compensating currents starts to work: γ_2 = 0.61 (γ_v = 1.12, row 5 of TABLE 1). The total current achieves the amplitude value at U = 5.5 kV and begins to decrease for some reason. In Ref. 33 it was shown that the current in photodischarge must continue to increase, because the decrease of U results in an increase of the efficiency of atom excitation by e-beams. In Ref. 20 it is stated that j decreases because of vanishing of the compensating currents. The cause is obviously confused with the effect. The vanishing of the compensating electron currents must be caused by the decrease of j, rather than by the reverse cause.

In general, it is unclear why the photodischarge requires the increase of U for the growth of the beam current and the efficiency (in particular, during the increase of the current, when, in the Bokhan and Bokhan's opinion,[20] the compensating currents are in force), as is observed in all the known experiments, including those with laser media. Another question is: why it is needed for the photodischarge at the decrease of the pressure and, consequently, the decrease of the e-beam interaction with a gas, to further decrease this interaction by increasing U to keep the same current[22]? All these examples reflect the properties of the glow discharge and do not fit the photodischarge.

2) Since for the photodischarge the coefficient of photoemission γ_v must be greater than unity (otherwise

the discharge does not start), the current must grow up to the value restricted by the "3/2" law. But such currents never take place in OD, as was noticed for the first time in Ref. 35. Recall that if the cathode emissivity is unlimited, the electrons leaving the cathode screen the field near the cathode and thus restrict the current according to the law $j \sim U^{3/2}$. This effect is observed for thermocathodes[9] and must be present in photodischarge. In Ref. 20 it is stated that in a gas-filled diode this law does not hold, and the current in this diode is lower than in a vacuum diode (two orders of magnitude lower in the presented example of the OD). This statement is wrong. In the presence of plasma, the positive volume charge near the cathode partly compensates for the spatial charge of the electrons, which results in the additional 1.86 times increase of the current through the diode.[9] So the failure of the "3/2" law in the example from Ref. 20 and in the data given in six rows of TABLE 1 for continuous and quasicontinuous OD (calculated $\gamma_v > 1$ everywhere!) indicates the absence of photodischarge.

In Ref. 20 it is also noted that the OD for the continuous and quasicontinuous modes is actually unstable, which agrees with its photoelectron nature. For suppression of the uncontrollable growth of the current, ballast resistances were used in Ref. 20. Similar effect was observed with the continuous OD in Ref. 37, but it is connected with the beginning of intense cathode spraying, rather than with the photoeffect. With the increasing voltage U of the continuous OD even in the presence of the ballast resistance, starting from some voltage U', the current increases drastically (without sparking and decrease of η), U drops down, the discharge in helium becomes blue, and the anode grid can melt if the discharge is not turned off. In the region of working voltages lower than U', the voltage–current characteristic is increasing, as in Ref. 20. For the photodischarge, the increase of the supply voltage must be accompanied by the increase of the current in the process of spontaneous decrease of U down to the value, at which γ_v becomes equal to unity. Similar effect of stabilization of U is present in the normal glow discharge. Since in OD this stabilization of U is not observed, the effect of photodischarge is absent in it.

3) In Ref. 22 [Fig. 4] it was noticed that the dependence of the current on the length of the discharge gap d = 1–10 mm in the OD is similar, as was shown in Ref. 3, to that of the glow discharge. This dependence, in which the current increases 47 times with increasing d, absolutely does not keep within the photodischarge. However, in Ref. 20 it is stated that with the increase of d, the parameter η drastically decreases because of alternation of the discharge mechanism. For the OD this means that the parameter η becomes much smaller than μ. In fact, the drastic decrease of η does not occur. In the experiments (p = 2.2 Torr, U_0 = 10.8 kV), as described in Ref. 22, the anode only in the central part was made as a grid with the area S' = 1 cm^2 and transparency μ' = 0.6. The area of the anode including the solid part was S = 2.1 cm^2, which corresponded to the transparency μ = 0.28. With the increase of d, the current increased, while the parameter η decreased, starting from $\eta \approx 1$ (for the photodischarge this means that the efficiency $\xi = \eta/\mu > 1$!). For d = 3 mm: $\eta = \mu' = 0.6$, the current increased 21 times! as compared to the initial value for d = 1 mm (where is the drastic decrease of η?). At a larger d, the discharge to the solid part of the anode was formed, which was clearly seen from the gas glow appearing there, and $\eta \to \mu$. The smallest value of the parameter η = 0.38 was even somewhat higher than the total geometric transparency of the anode μ = 0.28, which can be naturally attributed to the lower current density at the solid part of the anode, because there is no sag of the field there (in the typical OD the field is strong all over the gap; therefore, because of the field sagging, the cathode erosion caused by the cathode spraying is most noticeable near the axial lines of the openings of the grid-like anode, to which the ions are directed in their movement from the region of the sagged field). To avoid loose talk, let us present a more simple and illustrative example from Ref. 2, where the oscillograms depicted in Fig. 7*b* demonstrate that the drastic decrease of η does not occur under the conditions even more different from those typical of the OD: p = 3 Torr, d = 26 mm, when $\eta \approx \mu = 0.6$ as well.

4) For analysis of the experiments from Ref. 22, which show the independence of the total current j of the length of the drift space L, Bokhan and Bokhan[20] have invoked the calculations of γ_v from TABLE 1, which have demonstrated that under conditions of Ref. 22 for the photodischarge, j must not change. Let us leave this example and consider other experiments (from Ref. 8), in which one of the authors of Ref. 20 took part and where it was also demonstrated that j is independent of L if the full e-beam reaches the collector. The experimental conditions in Ref. 8 (p = 38 Torr, U = 4–8 kV), which are of interest for us, are similar to those given in row 5 of TABLE 1 (p = 30 Torr, U = 5.7 kV). The main contribution to γ_v = 1.12 must be due to the compensating currents: γ_2 = 0.61. The compensating current j_g depends on the charge carried by the e-beam into the drift region and dispersed there over its length L, that is $j \sim j_g \sim L$, which was not confirmed in the experiments.

Thus, some statements of Ref. 20, including the calculations of γ_v, deeply contradict each other and the photoelectron mechanism of the OD.

1.6. In Ref. 38 it was stated that, with the increase of the volume of the discharge cell, the mechanism of electron emission alternates in the abnormal glow discharge, namely, the mechanism of ion–electron emission is replaced by photoemission. This allows generation of high-power e-beams in simple devices with the efficiency $\eta > 0.9$ and low cathode spraying. The continuous discharge in different-size cells K1–K4 with the length L = 5.2, 10.3, 21.7, and 23 cm was initiated between the spherical cathode (radius of curvature R = 4.2, 10, 24, and 56 cm, cathode diameter

D = 1.75, 3.4, 7.6, and 17 cm) and the ring anode (inner opening ≈ D) spaced by 3 cm from it. Under conditions of the K4 cell: U = 0.36–1 kV, p_{Ne} = 0.3 Torr, it was obtained that $\eta = j_c/(j_c + j_a) = 0.96–0.99$. This parameter was interpreted as the efficiency of e-beam generation with the statement (referring to Ref. 20 discussed in detail above) that these values of η can be obtained only with the significant predominance of photoemission. Let us analyze the experiments of Ref. 38 from other positions.

1) Note, first of all, that in K4, for example, for U = 0.4 kV and p_{Ne} = 0.3 Torr, the depth of penetration of the e-beam with the electron energy of 0.4 keV, according to Ref. 39, is L_e = 12.5 cm, which is almost twice as small as L = 23 cm, and the e-beam does not reach the collector, though the experimentally measured parameter η is equal to 0.96. In any case, a significant part of the e-beam energy under considered conditions (U up to 1 kV) is absorbed in the gas, and so η can characterize neither the e-beam energy nor, for U < 0.8 kV, the e-beam current. The fact that negative charges decelerated from the e-beam and generated in the drift almost do not flow to the ring anode is indicative of the presence of the prevalent electric field on the whole path from the cathode to the collector, along which the negative charges move to the collector and the positive charges move to the cathode.

2) In the region of the working pressures[38] p_{Ne} = = 0.09–0.76 Torr, according to Eq. (4), $(l_{cf})_{AD}$ = 2.9–0.35 cm < d = 3 cm. However, for example, for p_{Ne} = 0.3 Torr in K2 the measured current j was several times lower than that determined by the equation for j_{AD} (equations like Eq. (3) for j_{AD} and different gases can be found in Ref. 40), which indicated that the discharge in K2 was still hindered. The increase of η (current j_c) observed in Ref. 38 with the increase of D (K1 → K4) can be attributed to weakening of the screening effect of the ring anode to penetration of the rest field behind the CD region toward the collector, extension of the discharge area to the collector, and the partial carry-over of the cathode potential by the e-beam beyond the ring anode. Note also that for large D the relative contribution of the direct current intercepted by the anode ring near the cathode wall decreases. With the increase of p_{Ne}, the discharge area extends as well, and j on the cathode surface equalizes, so the accompanying growth of η is observed in the experiments.

3) In Ref. 38, the current measured for K4 exceeded by an order of magnitude the j_{AD}, which was attributed to the large volume of K4, in which, in Bokhan and Zakrevsky's opinion, the density of the photoemission current exceeds the current due to cathode bombardment by heavy particles. The questions arises: why no similar effect is observed under conditions of quasicontinuous (τ = 200 ns) discharge in neon[41] (oscillograms in Fig. 2*a* in Ref. 41, U = 2.2 kV, p_{Ne} = 2.3 Torr), which are even more favorable for photoemission.

The cell in Ref. 41 had the coaxial design, which provided for the far better use of emission from atoms in drift for cathode illumination (radiation is lost only at the cell ends). The cathode area $S = 10^3$ cm^2 fourfold exceeded S in K4. The e-beam in the abnormal discharge (d = 4.5 mm > $(l_{cf})_{AD}$ = 3.2 mm) was almost fully absorbed at the drift length equal to the diameter of the cylindrical cathode (L = 9.9 cm, L_e = 10.7 cm). Nevertheless, the measured current j = 0.6 A/cm^2 was very close to j_{AD} = 0.53 A/cm^2.

At the same time, j exceeded j_{AD} 20 times under conditions that were worse for the photoemission[29] in the continuous discharge with the cathode area 23 times as small as that used in Ref. 38.

Likely, the excess of j over j_{AD} is connected with the effect of the cathode spraying, which manifests itself to the highest degree at the low pressure. In addition, Ne^+ ions in Ref. 38 must cause a more intense cathode spraying than He^+ ions do (roughly 100 times for the Al cathode used in Ref. 38).

1.7. From this analysis, which can be supplemented by the qualitative and illustrative pattern of e-beam formation in glow discharges of different kind from Refs. 2 and 3, it follows that the OD behavior represents the properties of the glow discharge rather than the photoelectron one. The OD involves the simplest and dense forms of the glow discharge,[2,3] of which the latter includes the abnormal discharge. The difference, though significant at the first sight, is not that important and can be explained from the positions of the glow discharge. This is observed in various glow-discharge devices with a complex geometry of the discharge gap and the electrodes, which allow some discharge properties to be separated and intensified in the aspect significant for the practical usage.

For example, in the OD with the parameter pd from the left branch of the Paschen curve, the presence of the field sag in the anode makes the discharge development easier and, at the same time, allows the discharge voltage to be varied widely up to the beginning of explosive processes on the cathode or intense cathode spraying. The cathode spraying can manifest itself in the increase of the current and in the stable conditions of pulsed and quasicontinuous OD, but the discharge is transformed into a continuous one at the same U, the current can continue its growth up to the discharge transition into the arc form.

The main requirement to the efficient e-beam generation in glow discharges is that, under conditions of maintaining the discharge stability, it is needed to maintain high values of the electric field and the potential drop in the near-cathode area for generation of a sufficient number of high-energy neutral atoms sustaining the efficient emission of electrons from the cathode.

As to the effect of photoemission on the OD, it shows itself at the initial, pre-breakdown stage of the discharge, providing for the uniform illumination of the cathode, which improves the OD stability.[33] The strong effect of photoemission at this stage is also known for the ordinary glow discharge.[25]

To summarize the above-said, I would like to cite Ref. 42, where it is said that sometimes it is difficult to answer the Pilate question "What is truth?" The point is only in a new selection of facts and their other interpretation. If we compare facts in a little bit different way, highlight some of them, shade others, focus on some facts, omit others – and the objective is already turned on its head... So we can see what is the value of indirect facts, even if they are very rigorously systematized.

2. Contribution of photoemission of electrons from the cathode in open discharge

2.1. The atom–electron emission from the cathode in the glow discharge is calculated in Ref. 1 for the cases of the simplest discharge, in which the field distortion in the discharge gap can be neglected, the abnormal discharge in the absence of a string field beyond the CD region, and under conditions, for which the distribution of the electric field in the OD was measured.[21,43] The calculations accounted for the cathode bombardment by ions and fast neutral atoms generated in the ion charge exchange processes, $\gamma_{ia} = \gamma_i + \Sigma\gamma_a$. The calculations turned out to be in a close agreement with the efficiency of e-beam generation in glow discharges, including OD. Thus, the radiant efficiency measured in Ref. 29 with calorimeters under conditions of abnormal discharge was 70% for $U = 2.4$ kV (no information about calorimetric measurements for $2.4 < U < 10$ kV is available), which is equal to the calculation by Eq. (6) and the equation for γ presented in Ref. 1:

$$\gamma \approx \gamma_{ia} = \gamma_i + \Sigma\gamma_a \approx -0.84 + 1.43 \cdot 10^{-3}\, U + 1.35 \cdot 10^{-8}\, U^2. \quad (7)$$

Note that the efficiency in Ref. 29 was independent of the anode position, even if it was far from the e-beam trajectory.

The calculations from Ref. 1 were called in question in Refs. 20 and 21. The calculations made in Ref. 21 for γ_{ia} in He with regard for the energy loss of fast atoms in elastic atomic collisions gave 2.3 to 3 times lower values of γ_{ia} than those in Ref. 1, where this loss was ignored (if we take into account that the appearance of the field near the cathode leads to the two to three times growth of γ, for example, for $E_c = 2 \cdot 10^5$ V/cm, typical of the OD,[9] then this difference is significantly compensated for). Even the large difference with the calculation of Ref. 1 was obtained in Ref. 20, where it was assumed, in particular, that $l_{cf} \sim \lambda_{ct}$ at $\gamma_a = 0$. An important question about the applicability of γ measured under conditions of technical or ultrahigh vacuum in the calculations was also formulated in Ref. 20. The data on the coefficients of electron emission from the cathode bombarded by fast ionized γ_i and neutral γ_a atoms, with the energy of tens and hundreds eV, can differ by one to two orders of magnitude depending on the measurement conditions: in ultrahigh ($p \le 10^{-9}$ Torr) [Refs. 44, 45] or technical ($p \gg 10^{-9}$ Torr) [Ref. 46] vacuum. The atoms with such energy are present in the most poorly studied glow discharges with the near-cathode potential drop from a few to ~10 kV, in particular, in the OD. According to the estimates made in Ref. 20, the values of γ_i and γ_a measured under conditions of technical vacuum and presented in Ref. 46 (they were used in the calculations in Ref. 1) do not correspond to the real discharge conditions and thus cannot be used.

The calculations in Ref. 1 are justified in detail and the objections from Refs. 20 and 21 are criticized in Ref. 6. In particular, it is noted that the parameter used in Ref. 21 is not the transport cross section of elastic scattering σ_{tr}, which characterizes the true energy loss of a flying particle,[25] but it is the approximate cross section of complete elastic scattering σ_{es}, and the estimates in Ref. 20 are based on the incorrect data on γ_{ia}. The issue concerning the impossibility of $l_{cf} \sim \lambda_{ct}$ in the OD has been discussed in Sect. 1.2.

Thus, we can repeat once again that the efficiency of the e-beam formation in the OD that was calculated in Ref. 1 with the allowance for only the atom–electron emission agrees well with the experimental data for the glow discharge, including OD. However, the lack of calculations or estimates of the direct contribution of photoelectrons starting from the cathode to the efficiency creates some suspicion and does not exclude the appearance of new "proofs" for the photoelectron nature of the OD. Let us try to fill this gap. The easiest way to do this is to estimate the needed energy w_s for escape of one photoelectron from the cathode.

2.2. Start from the lower estimates of w_s for a traditional OD with the ordinary grid-like anode. Restrict our consideration to only small cathode area ~1 cm^2, with which different authors studied the principal OD properties (this and the following conditions are not of the primary importance, and are used for a simplification). Take into account that the discharge characteristics do not vary as the region of e-beam drift behind the grid decreases down to 1 cm [Refs. 8, 22, 28, and 33]. In this case, only 1/6 of the total radiation reaches the cathode from the drift region. Assuming the same efficiency for excitation of the resonant level (21.2 eV), from which the principal contribution to photoemission is expected, and for ionization (24.6 eV) of helium, and taking the coefficient of photoemission $\gamma_p = 0.1$ [Ref. 36], we obtain for the needed energy: $w_s = (21.2 + 24.6\ \text{eV}) \times 6 \cdot 10 \approx 2.7$ keV. The real energy loss, for example, for a photoelectron with the energy $w = eU = 3$ keV flying from the discharge gap d into drift at $p_{He} = 8$ Torr and $dw/dx = 47$ eV/cm [Ref. 30] is $w_{rs} = 47$ eV. In the gap $d = 0.5$–1 mm the energy loss is much lower. Therefore, the photodischarge can be self-maintained under no conditions, neither at $eU < w_s$ nor at $eU > w_s$.

Thus, a single e-beam electron corresponds to no more than $w_{rs}/w_s = \gamma_v$ photoelectrons, their contribution to the efficiency is $\text{eff}_v \approx \gamma_v$, and we obtain $\text{eff}_v < 0.017$ for the lower estimate of the energy loss in the considered case.

2.3. In Refs. 27, 30, and 31, Bokhan and Zakrevsky have proposed a design, in which a grid of 3×5 mm^2 quartz plates spaced by a = 2–3 mm was placed at the distance of 1 mm from the cathode. The anode rods 2 mm in diameter were placed at the plate ends, that is, 6 mm far from the cathode. Bokhan and Zakrevsky believe that the discharge ions recombine on the walls of the dielectric grid and give no contribution to the anode current, while the discharge current is transported by photoelectrons from the cathode with the radiant efficiency up to 99.88%!

To find the lower estimate of w_s, assume that all ions contribute to photoemission through radiant recombination at the walls of the quartz plates. The radiation loss at the plates will be neglected. Then, unlike the case considered above, in which w_s = 2.7 keV, we obtain for the needed energy consumption ~$0.5w_s$ = 1.35 keV. In this case, at the supply voltage of U = 850 V, when, according to the measurements in Ref. 27, the efficiency is 99.2%, the photodischarge is impossible in principle. The allowance for screening of the radiation by the opening walls even further increases the needed energy w_s. Since the design is very poor for the cathode illumination, the radiation from the drift region can be neglected. The cathode receives only ~5% (a = 2 mm) of radiation of the excited atoms even from the entrance of the openings.

Thus, in this device the contribution of photoelectrons to the efficiency also turn out negligibly small. Moreover, the conditions of Refs. 27, 30, and 31 cannot ensure the observed high efficiency even due to the atom–electron emission on the assumption that the whole applied voltage is concentrated near the cathode. This is indicative of the incorrect technique of efficiency measurements, which is discussed thoroughly in Ref. 4.

Similar estimates are also valid for the conditions of abnormal discharge in neon,[38] which are considered in detail in Sect. 1.6. Thus, for U = 360 V, when η = 0.96 in Ref. 38, the escape of one photoelectron from the cathode requires the energy of 2.3 keV $\gg eU$ = 360 eV.

2.4. For a comparison, calculate the efficiency by Eqs. (6) and (7) for U = 3 kV. According to the equation, an ion, starting from the anode plasma and having passed through the CD region, together with the generated fast atoms ejects 3.6 electrons out of the cathode, which ensures eff_{ia} = 78%. (This is valid, if U is fully concentrated in the CD region, otherwise we should take into account the real distribution of the potential in the gap.[1]). In the detailed justification of the calculations made in Refs. 1,[6] it was emphasized that the calculations should necessarily use the emission coefficients measured under conditions of technical vacuum ($\gg 10^{-9}$ Torr). If γ measured in ultrahigh vacuum ($\leq 10^{-9}$ Torr) are involved, then, in the range of the supply voltage interesting for OD, the emission from fast neutral particles should be neglected and only the potential emission from ions should be taken into account. In this case, the efficiency does not exceed 20%. It is obvious that the conditions of ultrahigh vacuum are never fulfilled even before filling the discharge chamber with the gas under study.

Let us supplement the justification[6] for the calculations in Ref. 1 with the following illustrative example. In Ref. 28 it has been shown that the discharge with the ion–electron emission at the cathode as a sole secondary mechanism could not be initiated as the voltage exceeds some threshold U_0 because of ionizing capability of the electrons in the strong field decreases due to electron runaway. For example, in helium at pd = 1.5 Torr · cm U_0 is ~1.5 kV [Ref. 28]. Similar result follows also from the discharge initiation curves calculated in Refs. 47 and 48, where, in place of the traditional left branch of the Paschen curve, the curve again bends to the right, forming a loop. And only when Ul'yanov and Chulkov[47] have performed the calculations taking into account the cathode bombardment by fast neutral atoms responsible for the decisive contribution to the emission of electrons from the cathode, the result was in the left-hand branch of the Paschen curve, which coincided with the experiment. Ul'yanov and Chulkov[47] have used the same values of γ_i and γ_a, as those used in the calculations in Ref. 1, measured under conditions of technical vacuum.[46]

Conclusions

The estimates presented have shown that the contribution of photoemission to the total emission of electrons from the cathode is negligibly small. These estimates along with the performed analysis of the publications concerning the open discharge suggest finally that the open discharge is a sort of the glow discharge, which, as commonly accepted, is maintained by the atom–electron emission from the cathode and the ionization processes. So the most practically important conclusion is that the very rich material concerning the open discharge (more than 100 publications), with the appropriate correction of the experimental results, can be directly applied to the glow discharge in general, first of all, in the range of medium pressure: from a few Torr to the atmospheric pressure,[49] which has not been studied for glow discharge e-beams.

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